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Recent biomass burning in the tropics and related changes in tropospheric ozone

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[1] Biomass burning in the tropics is set intentionally during dry season each year to destroy agricultural waste and clear land for human expansion. These burning activities cause pollution including atmospheric particulates and trace gases which are harmful to human health. Measurements from the Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) from October 2004–November 2008 are used to evaluate the effects of biomass burning on tropical tropospheric ozone in the context of the Global Modeling Initiative (GMI) chemical transport model. The impact of biomass burning on ozone is significant within and near the burning regions with increases of ~10–25% in tropospheric column ozone relative to average background concentrations. Globally the model indicates increases of ~4–5% in ozone, ~7–9% in NO_x ($NO + NO_2$), and ~30–40% in CO. **Citation:** Ziemke, J. R., S. Chandra, B. N. Duncan, M. R. Schoeberl, O. Torres, M. R. Damon, and P. K. Bhartia (2009), Recent biomass burning in the tropics and related changes in tropospheric ozone, *Geophys. Res. Lett.*, *36*, L15819, doi:10.1029/2009GL039303.

1. Introduction

[2] Biomass burning is an important source of chemical precursors of tropospheric ozone [e.g., *Fishman et al.*, 1996; *Jacob et al.*, 1996; *Thompson et al.*, 1996, and references therein]. In the tropics, biomass burning produces ozone enhancements over broad regions of Indonesia, Africa, and South America including Brazil. Fires are intentionally set in these regions during the dry season each year to clear cropland and to clear land for human/industrial expansion. In Indonesia enhanced burning occurs during dry El Niño conditions such as in 1997 and 2006 [e.g., *Chandra et al.*, 1998; *Logan et al.*, 2008; *Chandra et al.*, 2009]. Biomass burning yields large amounts of atmospheric particulates and other important byproducts including CO_2, CO, N_2O, CH_4, NO_x ($NO + NO_2$), and non-methane hydrocarbons (NMHCs). The production of tropospheric ozone follows from oxidation of volatile organic compounds (VOCs), CH_4, and CO in the presence of NO_x and sunlight.

[3] High tropospheric ozone concentrations measured in the tropical south Atlantic during dry burning season (~August–November) has generated many observational studies suggesting biomass burning emissions as a significant if not dominant source for ozone [e.g., *Logan and Kirchhoff*, 1986; *Fishman et al.*, 1990; *Thompson et al.*, 1996; *Mauzerall et al.*, 1998]. *Mauzerall et al.* [1998] argued that biomass burning alone could fully explain these ozone enhancements during the dry season. Many recent studies based upon 3D chemistry and transport models have evaluated the effects of biomass burning on tropospheric ozone [e.g., *Moxim and Levy*, 2000; *Lelieveld and Dentener*, 2000; *Marufu et al.*, 2000; *Martin et al.*, 2007; *Sauvage et al.*, 2007]. These studies suggest that biomass burning has a less important role in ozone production than in previous studies. Recent fire events in the tropics show large interannual variability in the South American region. In year 2008 biomass burning in Brazil decreased significantly compared to year 2007 possibly due to government regulatory control. The reduction of fires from 2007 to 2008 in Brazil was estimated to be about 62% by O. Torres et al. (The anomalous 2008 Southern Hemisphere biomass burning season, submitted to *Atmospheric Chemistry and Physics*, 2009) using Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer/3 (AVHRR/3) fire counts. The objective of this paper is to study recent biomass burning events in the tropics including those in Brazil and their effects on tropospheric ozone using measurements of ozone and aerosol index (AI) from the Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS). These satellite measurements are studied in the context of the Global Modeling Initiative (GMI) chemistry and transport model developed at NASA Goddard Space Flight Center.

2. Satellite Measurements of Biomass Burning Aerosols and Tropospheric Ozone

[4] Daily measurements of tropospheric column ozone (TCO) and mean volume mixing ratio (VMR) are determined from OMI v8.5 total column ozone and MLS v2.2 stratospheric column ozone using a residual method [*Ziemke et al.*, 2006]. On average, 30 DU in TCO in the tropics corresponds to about 42 ppbv in VMR. Biomass burning events are often identified from satellite measurements of fire counts or aerosols. AI measured from OMI [*Torres et al.*, 2007] is a unit-less parameter that indicates the presence of UV-absorbing aerosols in the atmosphere such as carbonaceous aerosols generated by biomass burning. We use AI from OMI as a proxy of biomass burning since it has the same temporal and spatial coverage as derived tropospheric ozone. Both AI and tropospheric ozone daily measurements are averaged monthly for October 2004–November 2008 at $1° \times 1.25°$ resolution. The preci-

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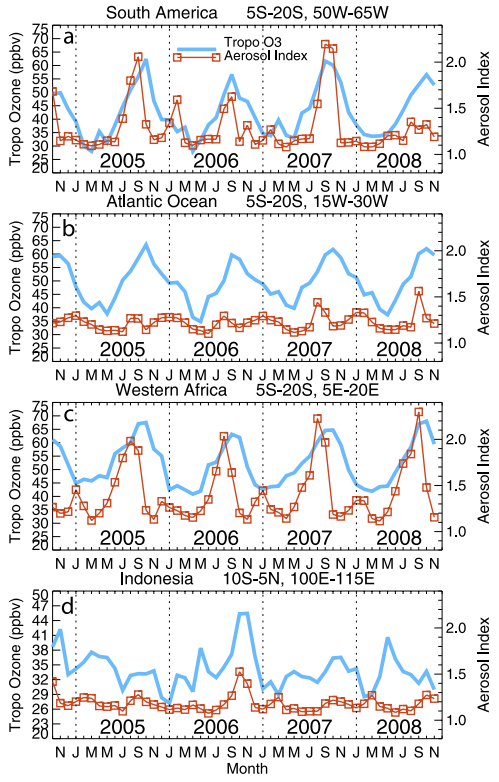

Figure 1. Time series of tropospheric ozone mean VMR (in ppbv) and AI averaged over four broad 15° × 15° regions (indicated) in the southern tropics: (a) South America, (b) Atlantic Ocean, (c) western Africa, and (d) Indonesia. The vertical scale for Indonesia is different than the other three regions for better visualization.

sion uncertainty for derived gridded ozone at 1° latitude by 1.25° longitude resolution is 5 DU (7 ppbv) with mean offset of 2 DU (OMI/MLS larger). Time series of ozone and AI were determined by averaging measurements over broad 15° × 15° regions; this averaging reduces precision errors in ozone to less than 1 ppbv.

[5] Figure 1 shows time series of ozone VMR and AI centered over several regions in the tropics where smoke from biomass burning is almost an annual event. These regions comprise countries in South America (SA) including Brazil (Figure 1a), western Africa (WA, Figure 1c), and several islands in Indonesia (Figure 1d). Also included is a region over the South Atlantic Ocean (AO, Figure 1b) where the effect of fire is indirect via transport from the burning regions of SA and WA. Figure 2 shows the distribution of ozone for September 2007 along with these four defined regions (indicated by rectangular boxes).

[6] Figures 1a–1c (SA, AO, WP) have similar seasonal patterns in ozone with maximum values in September-October and minimum values in March-April. For Indonesia there is not a clear seasonal pattern, but there is enhanced ozone during the 2006 El Niño event which is caused in part from biomass burning in the region [*Chandra et al.*, 2009]. The seasonal patterns in ozone, both in SA and WA regions are similar but with a phase lag of 1–2 months with respect to AI. An analysis of tropospheric NO_2 from OMI [*Bucsela et al.*, 2006] (E. Celarier, personal communication, 2009) and the GMI model (discussed in section 3) also indicates a 1–2 month phase lag between peak NO_2 from the fires and peak ozone (figures not shown). The model suggests that the phase lags are related to a time delay effect in the photochemical production of ozone involving precursors and transport.

[7] Inter-annual changes in AI are generally larger than ozone. This is particularly apparent for the SA region (Figure 1a) where AI decreased from a peak value of about 2.2 in September 2007 to about 1.3 in September 2008. The OMI NO_2 measurements also indicate a reduction of NO_2 for this region (figure not shown). Between September 2007 and September 2008 NO_2 reduced by 30% (i.e., 1.35×10^{15} to 0.95×10^{15} molecules – cm^{-2}). The corresponding decrease in ozone is about 5–10 ppbv reflecting a decrease of about 10–15%.

3. GMI Model Analysis of Biomass Burning Events and Tropospheric Ozone

[8] The GMI chemistry and transport model is described in detail by *Duncan et al.* [2007] and *Strahan et al.* [2007]. The emissions of trace gases and the aerosol fields used in the simulations presented in this manuscript are described by *Duncan et al.* [2008], except for the biomass burning emissions which are described by *van der Werf et al.* [2006]. Time appropriate anthropogenic and biomass global emissions include surface emissions from industry/fossil fuel, biomass burning, biofuel combustion, and contributions from aircraft. A validation of the model is given by *Chandra*

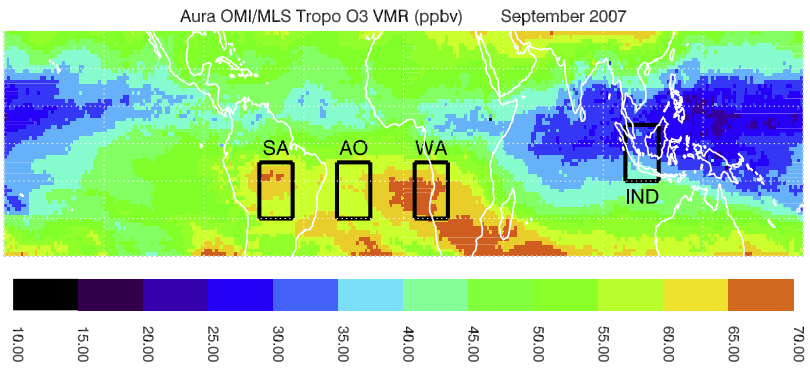

Figure 2. OMI tropospheric ozone mean VMR (in ppbv) for September 2007. The four 15° × 15° regions selected for study are shown by the rectangular boxes.

Table 1. Global Budget of CO and NO for 2006 With and Without Biomass Burning[a]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO(wBB)	91.5	72.4	80.9	67.1	72.2	75.8	98.4	119.1	117.1	117.0	85.2	103.2
CO(w/oBB)	61.8	55.2	59.1	53.0	52.1	54.1	58.0	58.3	55.5	58.9	59.0	61.1
NO(wBB)	6.6	5.7	6.2	6.0	6.5	6.6	7.4	7.7	7.1	7.1	6.4	7.1
NO(w/oBB)	5.7	5.3	5.8	5.6	6.0	6.0	6.2	6.2	5.6	5.9	5.7	5.8

[a]Units are in teragrams (Tg); T $\equiv 10^{12}$.

et al. [2009] where zonal and seasonal/inter-annual variability of tropospheric ozone from the model was compared with measurements from OMI/MLS. The comparisons which include the months October 2004 to December 2006 showed that the measurements and model agree well in temporal and spatial variability from the tropics out to mid-latitudes. Mean offset differences and RMS of the differences average ~5 DU with worst comparisons ~5–10 DU in northern mid-latitudes during winter-spring. In general, GMI ozone is lower (higher) than OMI/MLS in the tropics (extra-tropics) by ~5DU. Most of the discrepancies in the tropics occur in regions of biomass burning. Surface emission inventories as input to the GMI model for year 2008 are not yet available. For this reason we cannot use the model to study biomass burning in 2008. Instead we have chosen 2006 to evaluate the effects on ozone from biomass burning in the WA and SA regions, and Indonesia (i.e., 2006 was an El Nino year with substantial biomass burning in Indonesia).

[9] The model was run for 2006 with two scenarios: (1) with biomass burning emissions (wBB) and (2) without biomass burning emissions (w/oBB). Table 1 shows monthly global budgets of CO and NO_x from the model for these two model runs. Most of the increases in CO and NO_x lie in the tropics with values ~100% and ~25%, respectively, during August-October months when burning is intense.

[10] Figure 3 compares observed seasonal cycles in ozone VMR with ozone from the two model runs. The regions in Figure 3 are the same as those in Figures 1 and 2. The difference between the two model runs is interpreted as an estimate of ozone generated from biomass burning. The wBB run produces the observed seasonal cycles in all four regions, especially for the AO region which lies far away from burning sources. Figure 3 indicates that an anomalous increase occurred in measured ozone in May 2006 in the Indonesian region. This ozone increase has also been observed in Tropospheric Emission Spectrometer (TES) data with values comparable to OMI/MLS (J. Logan, personal communication, 2009). The GMI model in Figure 3 also indicates a relative increase in ozone in May 2006 but it is ~5 ppbv smaller than OMI/MLS. The model suggests from differencing the two model runs that this May anomaly is not associated with biomass burning.

[11] There are noticeable differences in Figure 3 in VMR between the model and measurements in the SA and WA regions during the burning months of August-November. In both of these regions the model underestimates observations by 5–8 ppbv (about 10–15%) between measurement (black curves) and wBB model (blue curves). In the Indonesian region the differences during these months are smaller (2–4 ppbv, or about 5–10%). In the burning regions the smaller values of ozone for the model may be caused by an underestimation of the burning inventories and/or uncertainties in the model such as emission injection heights and emission ratios for NOx versus VOC. It is a general result that away from the immediate burning regions the agreement between the model and measurements is much improved such as over the Atlantic Ocean (e.g., Figure 3b).

[12] The spatial extent of the regions affected by biomass burning in the tropics is shown in Figure 4 using the model runs with the two scenarios. Figure 4 suggests that biomass burning contributes to about 10–20% increases in VMR during austral spring in the African and South American regions. These are likely lower limits if we assume that the burning inventories in the model are underestimated. In Indonesia the relative contribution of biomass burning is somewhat larger, ~15–25% in the burning region and

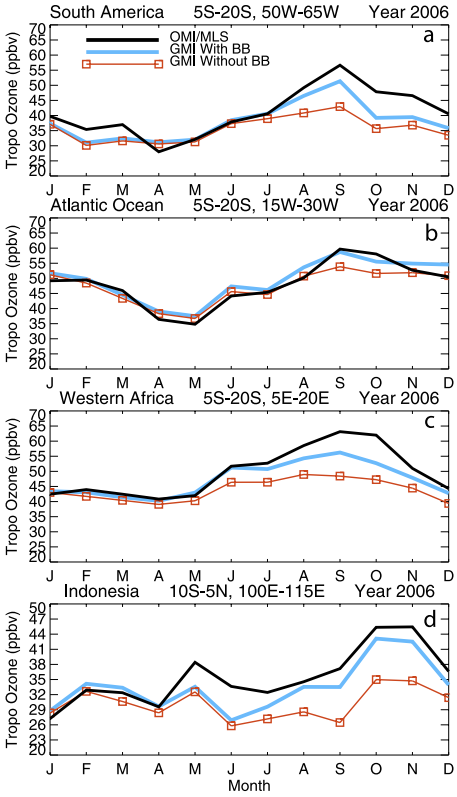

Figure 3. Time series of tropospheric ozone mean mixing ratio (in ppbv) for year 2006 from two GMI model runs: full model run (blue curves) and the model run without emissions (red curves with boxes). The black curves are OMI/MLS tropospheric ozone. These four regions are the same as those in Figures 1 and 2. The vertical scale for Indonesia is different than the other three regions for better visualization.

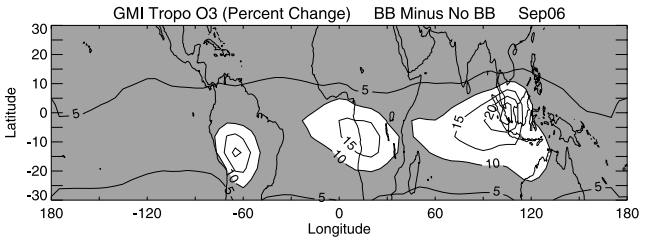

Figure 4. Contour diagram showing percentage change in tropospheric ozone mean mixing ratio from biomass burning from the GMI model for September 2006 when large contributions for all three burning regions in Figures 2 and 3 occurred. Values less than 10% are shaded.

extending over a larger area at the 10–15% level than the regions SA and WA. The increase in ozone in Indonesia is, however, episodic and induced by the dry conditions during the 2006 El Niño event.

[13] Our analysis supports previous claims that biomass burning is a significant source for generating tropospheric ozone in the tropics, but small when compared to lightning and transport in the troposphere [e.g., *Martin et al.*, 2007; *Sauvage et al.*, 2007]. *Martin et al.* [2007] indicated that more than 40% of tropospheric ozone throughout much of the tropics is generated from lightning. *Sauvage et al.* [2007] concluded that lightning is about 4–6 times more efficient in producing ozone than the combined effects of biomass burning, soils, and fossil fuels.

[14] From a global perspective, the GMI model for year 2006 indicates that biomass burning caused a maximum of about 4–5% increase in global tropospheric ozone with most contribution coming from the tropics. About half of these ozone changes in tropospheric ozone came from biomass burning in Indonesia during the 2006 El Niño which alone increased ozone globally by 2–3% [*Chandra et al.*, 2009]. Although biomass burning does not generate large amounts of ozone in a global sense, the burning yields larger increases in other important trace gases. Biomass burning for year 2006 from the model indicates global increases of 7–9% in NO_x and 30–40% in CO during the months of most intense burning.

4. Summary

[15] We have studied the effects of biomass burning on tropospheric ozone in the tropics derived from Aura OMI/MLS ozone measurements for the time period October 2004–November 2008. Biomass burning in many regions in the tropics is intentionally set each year during the dry season to destroy agricultural waste material and clear land for human expansion. Anthropogenic burning was reduced substantially in Brazil in year 2008 compared to previous years including 2007. The OMI/MLS measurements show sizeable decreases ~15–20% in ozone in Brazil during 2008 compared to 2007 which we attribute to this reduction in biomass burning.

[16] Three broad biomass burning regions in the tropics (South America including Brazil, western Africa, and Indonesia) were analyzed in the context of OMI/MLS measurements and the GMI chemistry and transport model. The results indicate that biomass burning in these three regions contributed to mean increases in tropospheric ozone by 8–10 ppbv over mean values of 35–55 ppbv in the months of August-November. (In column amount this corresponds to about 6–7 DU relative to mean values of about 25–40 DU.) Tropospheric ozone produced from biomass burning is primarily a regional effect within and near the burning with most generated ozone lying in the low troposphere. The model suggests that about half of the increases in ozone from these burning events come from altitudes below 3 km. Our study substantiates previous claims that biomass burning is a significant source of generating tropospheric ozone in the tropics, but it is small when compared to the effects from lightning and transport in the troposphere.

[17] The GMI model for year 2006 shows a 4–5% increase in global tropospheric ozone caused by biomass burning with most contribution coming from the tropics. Nearly half of these increases originated from Indonesian fires during dry El Niño-induced conditions. Globally, biomass burning does not produce large amounts of ozone, but it does yield large increases in other important constituents. The model indicates global increases of 7–9% in NO_x and 30–40% in CO during the months of greatest burning.

[18] **Acknowledgments.** The authors thank the Aura OMI and MLS instrument and algorithm teams for producing the satellite ozone and aerosol measurements used in this study. We also thank the GMI group members for their efforts in generating their extensive 3D chemistry and transport model trace gas results including ozone. Funding for this research was provided in part by Goddard Earth Science Technology (GEST) grant NGC5-494.

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